

SmallSat Navigation via the Deep Space Network: Inner Solar System Missions

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The CubeSat Revolution

<https://www.jpl.nasa.gov/cubesat/info.php>

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search

MarCO: 2 CubeSats to Mars
EM-1: >10 SmallSats
After: ???

DSN

A New Revolution in Spacecraft - The CubeSat Era

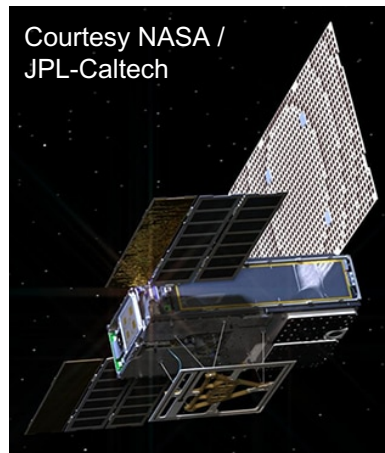
Courtesy NASA / JPL-Caltech

A Catalogue of DSN Support Options

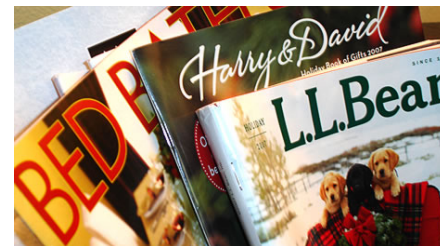
Radiometric Tracking & Orbit Determination Performance

Rough order-of-magnitude estimates

- Main DSN data types:
 - Doppler & ranging (line-of-sight)
 - Two-way = gold standard
 - DDOR / VLBI (plane-of-sky)
- Variations:
 - Pass sub-sampling
 - X- and Ka-band (no major difference)
 - One-way Doppler & range:
 - [Opportunistic] Multiple Spacecraft Per Aperture (MSPA)
 - CSAC enabled (SA.45S - Symmetricom)
 - On-board clock modeling required

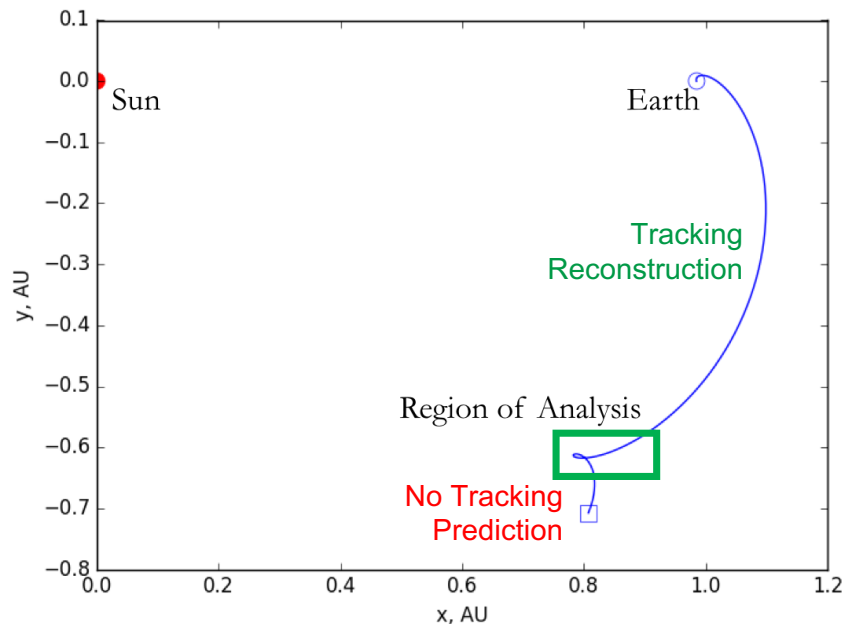


Courtesy NASA / JPL-Caltech

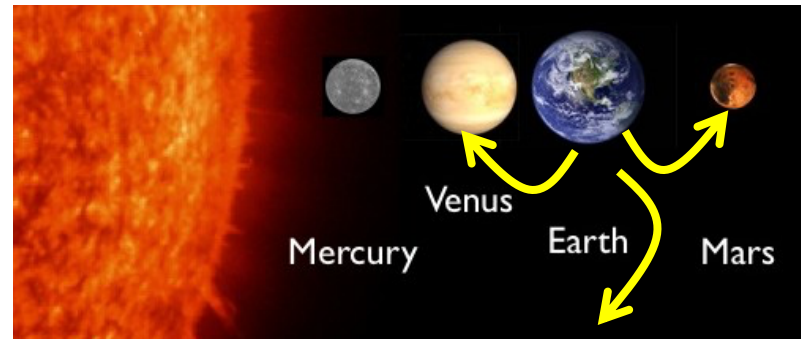


Reference Mission Scenario

Earth-trailing orbit



Sun-Earth Synodic Frame

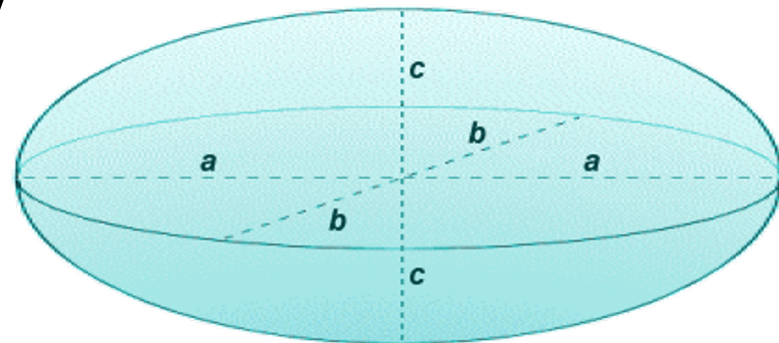
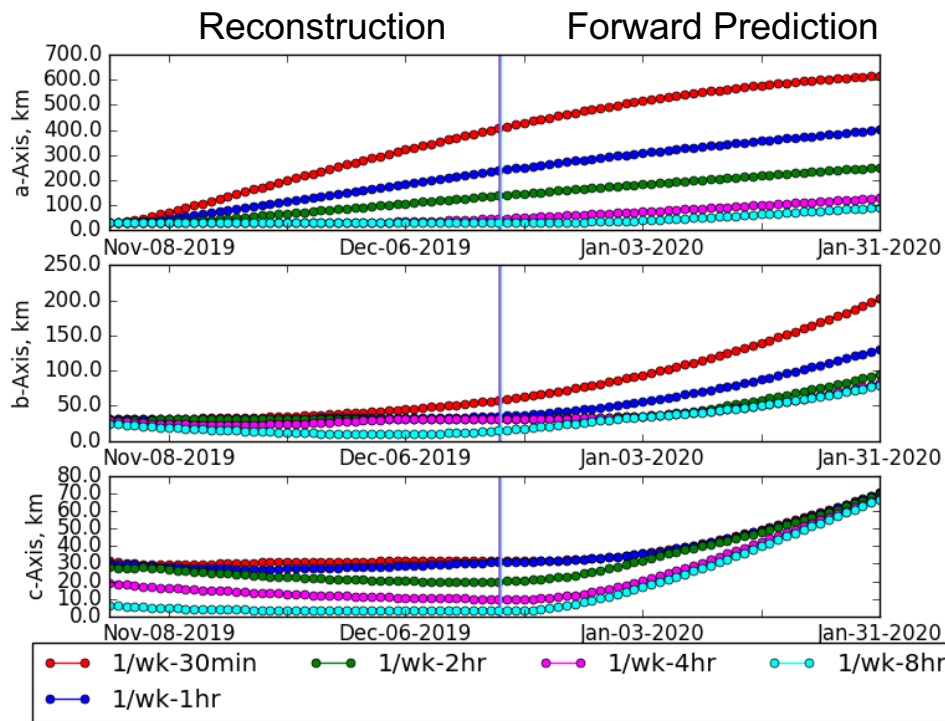


Consider Covariance Study:

- Tracking schedule
 - Pass frequency
 - Duration per pass
- Gravity
- Unbalanced attitude control
- Stochastic Accelerations
- Measurement errors
- Clock errors (one-way Doppler & range)

Position Uncertainty Time History

2-way Doppler only, 1 pass / week

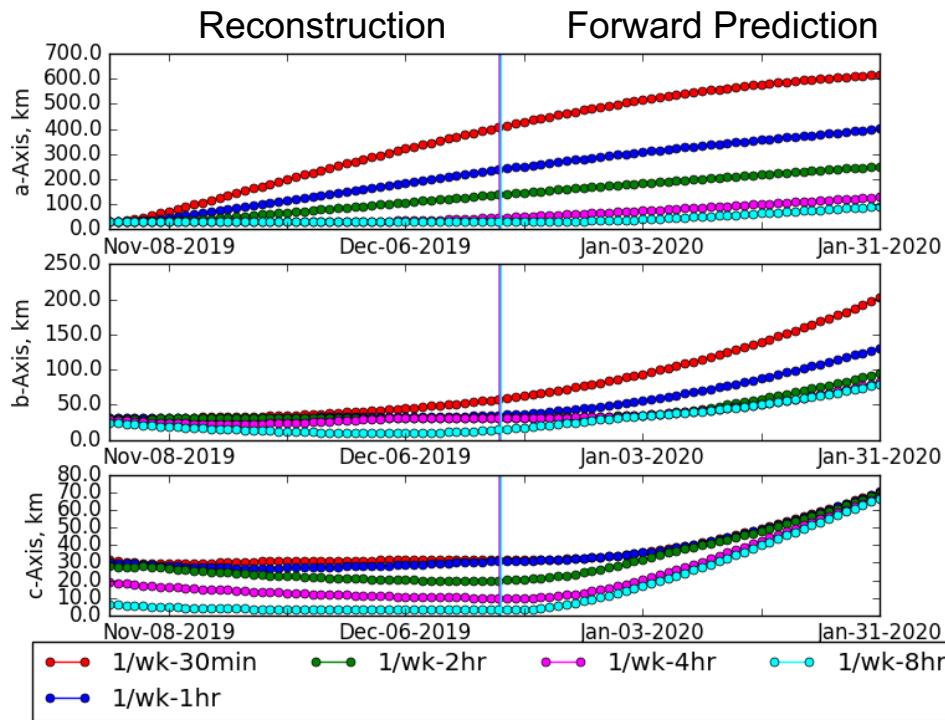


Forward Prediction

Analysis Case	Uncertainty RMS (km)
1/week, 30-min	650
Average	330
1/week, 8-hr	140

(Grossly Simplified) Result Comparison

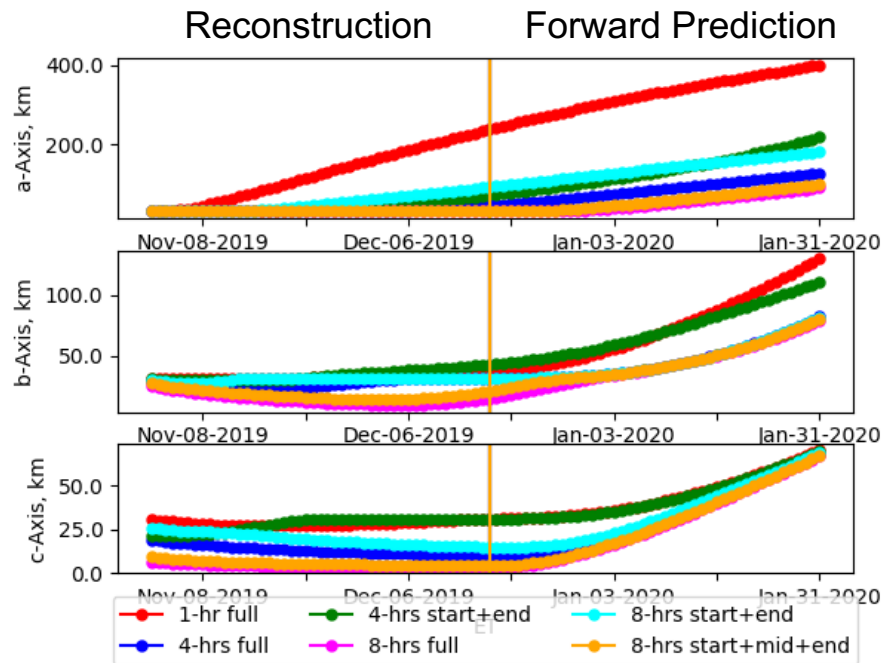
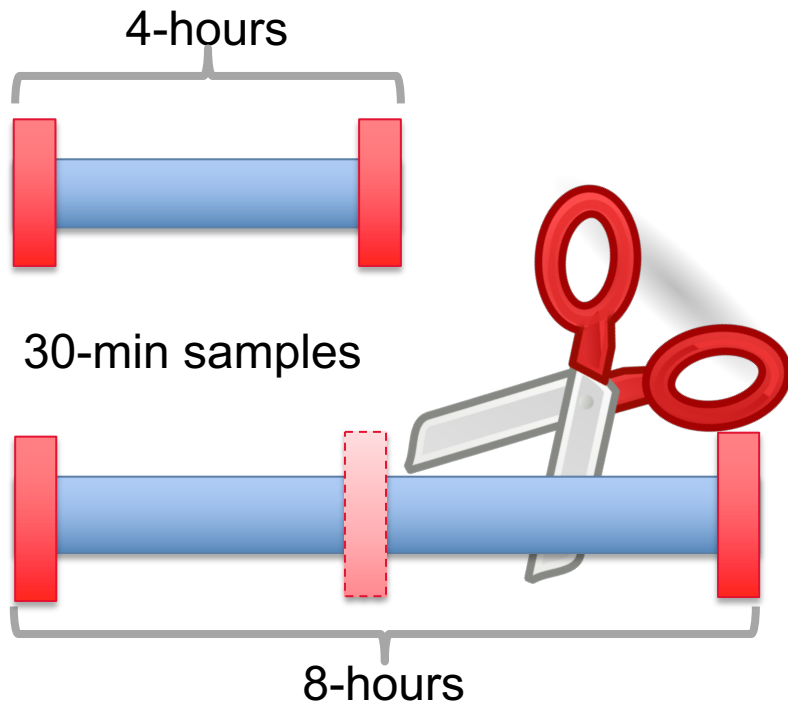
Exhaustive tabulated results & sample images in paper



Analysis Case	Reconstruction	Prediction
2-way Doppler	100%	100%
+ Range	50% (sparse) 10% (dense)	50% (sparse) 100% (dense)
+ DDOR (monthly)	25% (sparse) 100% (dense)	25% (sparse) 100% (dense)
1-way Doppler	700% (sparse) 200% (dense)	700% (sparse) 125% (dense)
+ Range*	75% (sparse) 25% (dense)	75% (sparse) 100% (dense)
+ DDOR (monthly)	50% (sparse) 300% (dense)	50% (sparse) 200% (dense)

Pass Sub-Sampling Strategy

Enabled by MSPA, clustered spacecraft flight

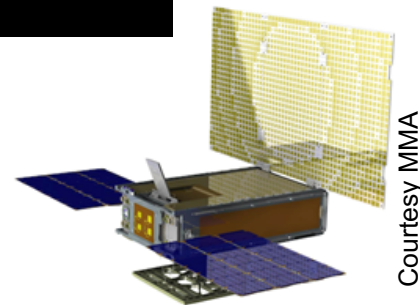


Summary

Mitigate cost & availability of DSN support



- Uncertainties vary by data type, tracking schedule
 - **Reconstruction:** $3000 \text{ km} \Rightarrow 2 \text{ km}$, $0.6 \text{ m/s} \Rightarrow 6 \text{ mm/s}$
 - **Prediction:** $4150 \text{ km} \Rightarrow 90 \text{ km}$, $0.1 \text{ m/s} \Rightarrow 4.5 \text{ cm/s}$
- Many possible combinations to give similar state knowledge
 - Longer tracking passes > more frequent passes
 - Doppler + range ~ Doppler + DDOR
 - Sub-sampling comparable to monolithic passes
- 2-way > 1-way
 - Opportunistic MSPA increases 1-way availability
 - Requires use of CSAC or similarly precise timing system
- **NOTE:** Results only valid for interplanetary cruise



Courtesy MMA



Courtesy NASA / JPL-Caltech

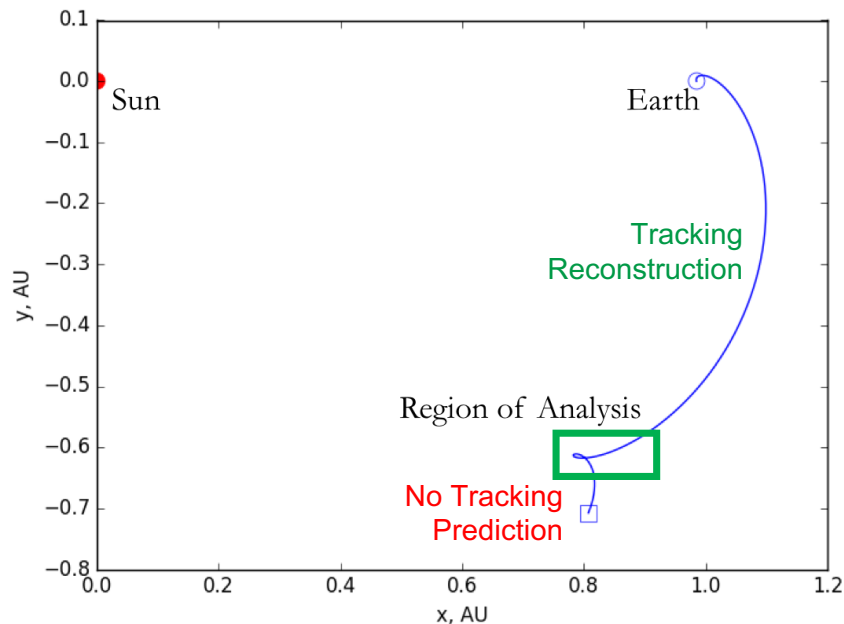


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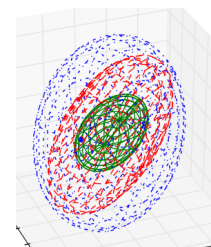
Reference Mission Scenario

Approach to lunar flyby



Sun-Earth Synodic Frame

Parameter	Value	Units
X-band frequency	7.99	Hz
Ka-band frequency	32.09	Hz
Two-way Doppler noise (X)	5.62-3	Hz
Two-way Doppler noise (Ka)	2.15-2	Hz
Two-way SRA noise (X)	1.0	m
One-way Doppler noise (X)	8.17-2	Hz
One-way range noise (X)	5.0	m
CSAC white noise (1-day)	2.15-3	Hz
CSAC random walk (1-day)	6.44-2	Hz
CSAC Allan deviation (1-day)	4-11	s/s
DDOR noise (X)	0.06	ns



Sample Tabular Results

2-way Doppler Only

*Position Uncertainty (km) - **Reconstruction** @ Data Cut-Off*

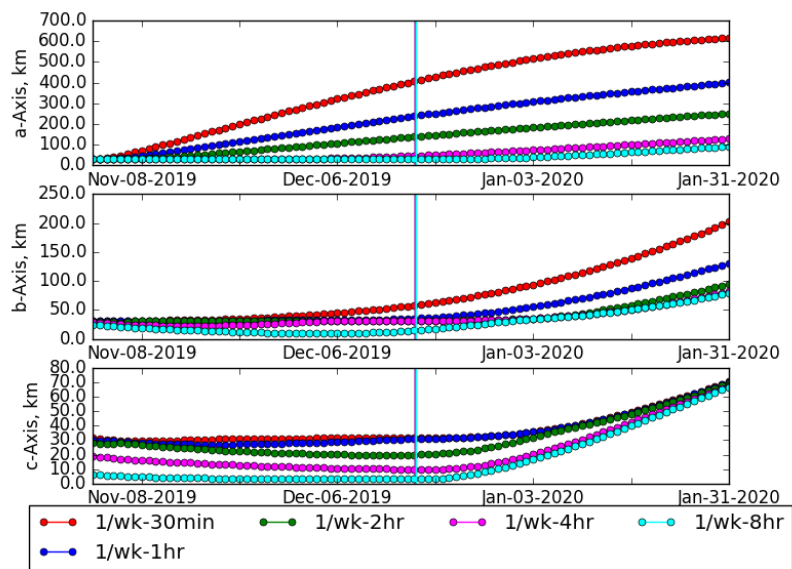
Passes Per Week	Pass Duration				
	30 min.	1 hr.	2 hrs.	4 hrs.	8 hrs.
1	(406.8, 58.26, 31.48)	(237.49, 35.27, 30.85)	(138.26, 31.77, 19.99)	(46.57, 31.46, 9.87)	(31.73, 14.68, 3.24)
2	(251.17, 31.82, 18.92)	(94.79, 31.79, 18.52)	(42.6, 31.64, 16.26)	(31.15, 21.45, 6.81)	(28.85, 10.26, 2.06)
3	(196.26, 31.69, 16.66)	(79.94, 31.64, 16.29)	(36.88, 31.23, 14.23)	(30.58, 18.11, 5.54)	(26.55, 9.03, 1.77)
7	(105.59, 30.89, 12.42)	(55.39, 30.61, 10.88)	(30.46, 27.72, 8.02)	(28.79, 13.2, 3.24)	(21.34, 5.47, 1.25)

*Position Uncertainty (km) - **Prediction** @ 6-weeks out*

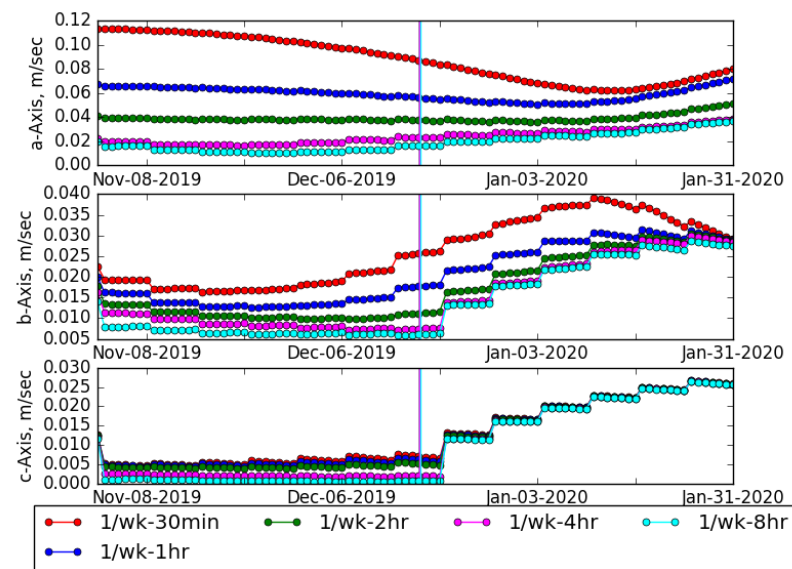
Passes Per Week	Pass Duration				
	30 min.	1 hr.	2 hrs.	4 hrs.	8 hrs.
1	(615.9, 202.2, 70.5)	(400.1, 130.5, 70.0)	(251.1, 94.6, 69.3)	(127.8, 82.2, 67.5)	(90.9, 79.3, 66.7)
2	(357.8, 80.1, 57.2)	(168.5, 78.2, 57.1)	(113.8, 71.0, 56.6)	(91.4, 64.3, 54.3)	(75.4, 61.9, 53.2)
3	(278.9, 62.6, 56.2)	(147.9, 62.6, 56.0)	(103.5, 62.4, 55.4)	(82.6, 62.0, 53.5)	(69.7, 59.9, 52.7)
7	(170.0, 61.6, 55.1)	(121.0, 61.6, 54.5)	(92.3, 61.5, 53.9)	(73.5, 60.9, 53.1)	(61.4, 58.2, 52.0)

Position & Velocity Uncertainty Time History

2-way Doppler only, 1 pass / week



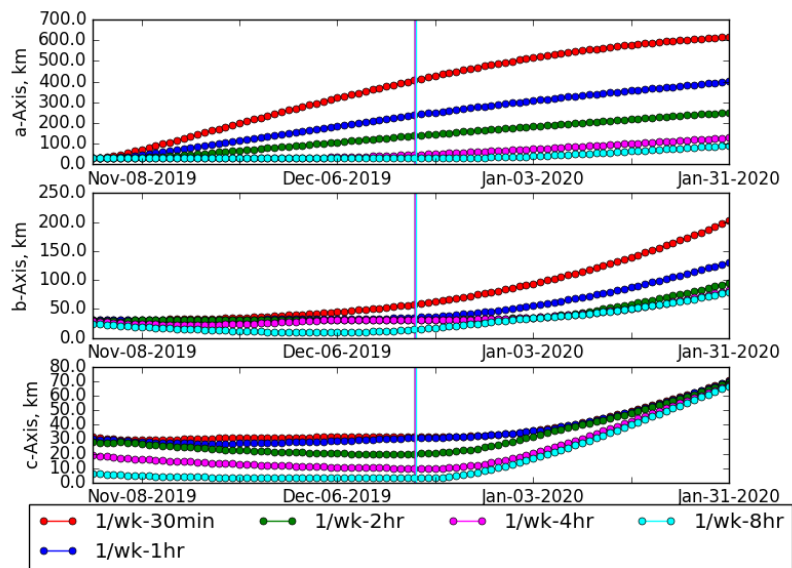
Position Uncertainty



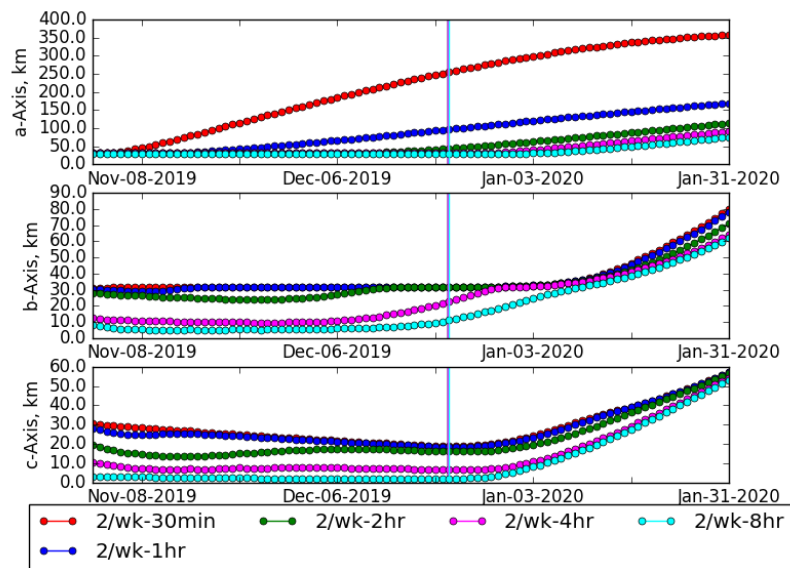
Velocity Uncertainty

Pass Frequency

2-way Doppler only



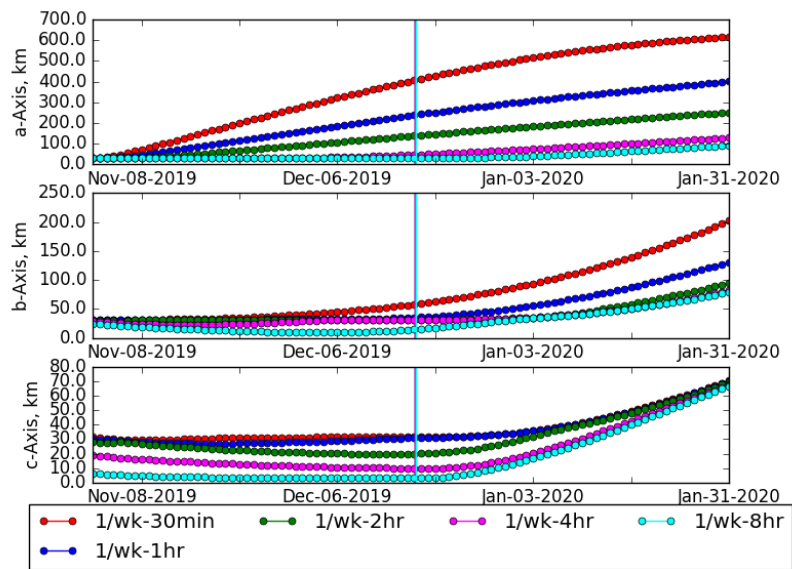
1 pass / week



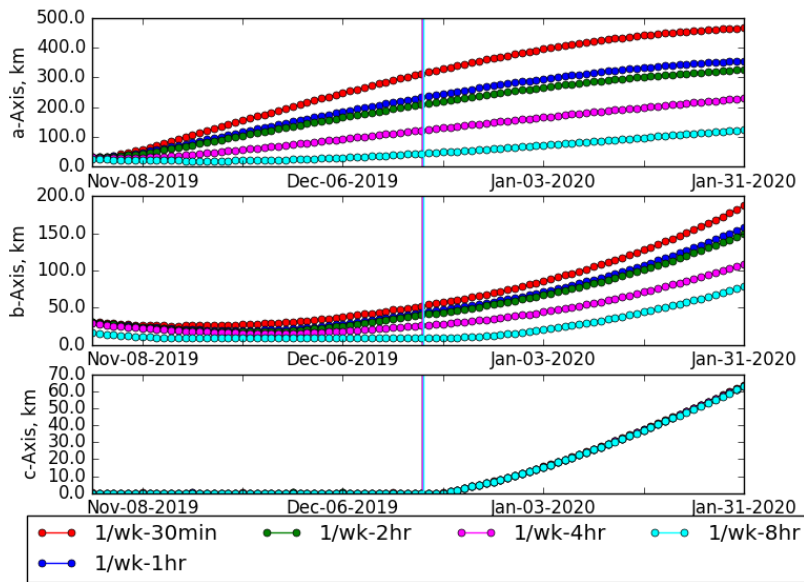
2 passes / week

Doppler vs Range

2-way, 1 pass / week



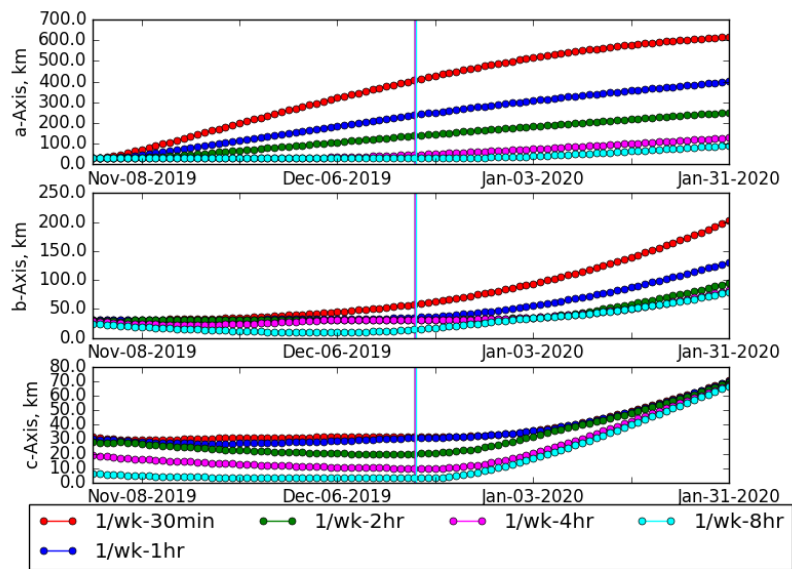
Doppler Only



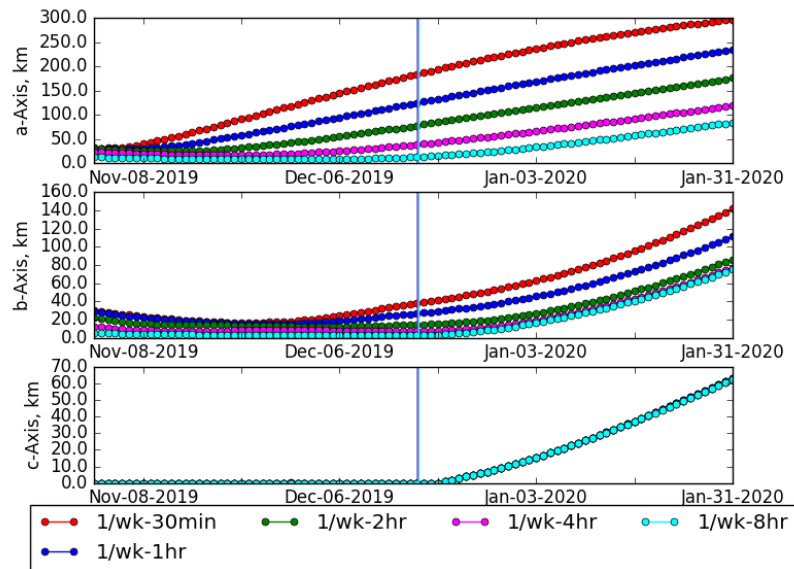
Range Only

Doppler + Range

2-way, 1 pass / week



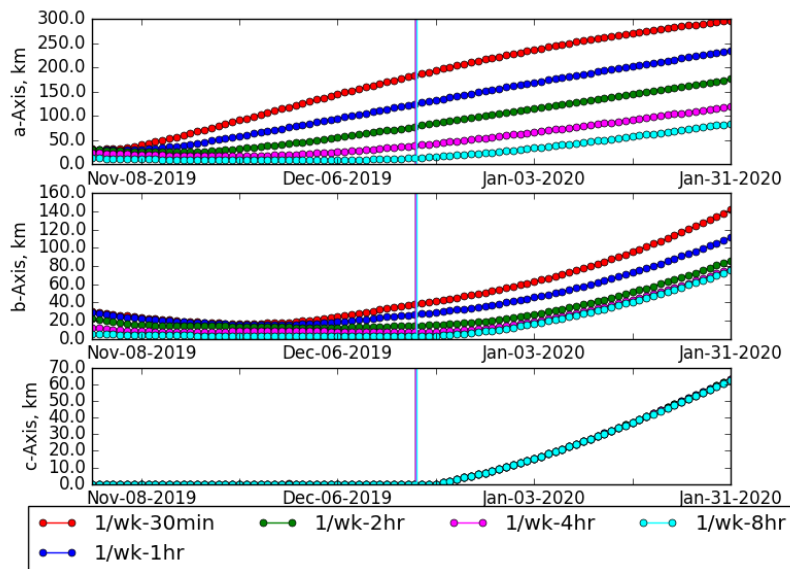
Doppler Only



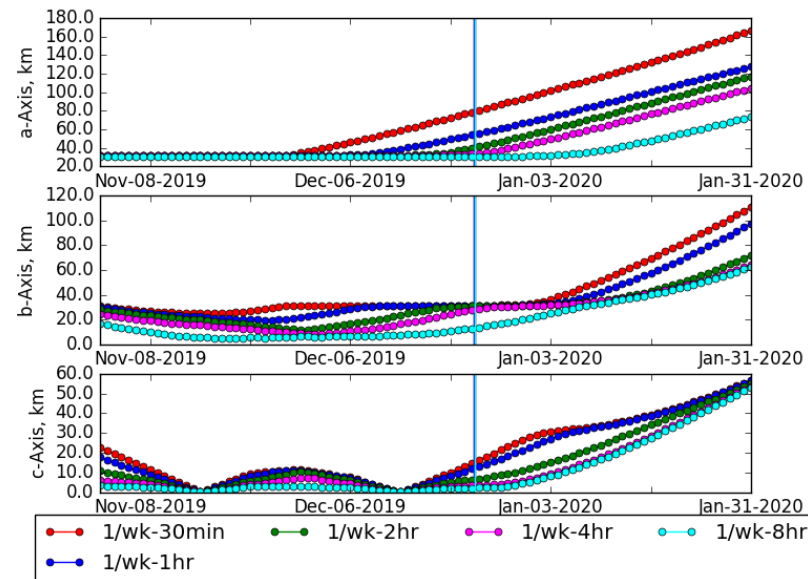
Doppler + Range

Adding Range/DDOR to Doppler

2-way, 1 pass / week, 1 DDOR / month



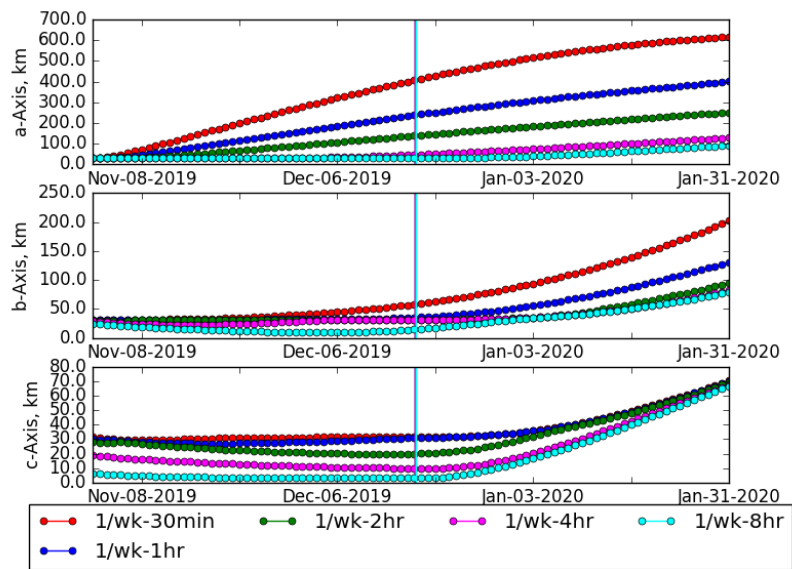
Doppler + Range



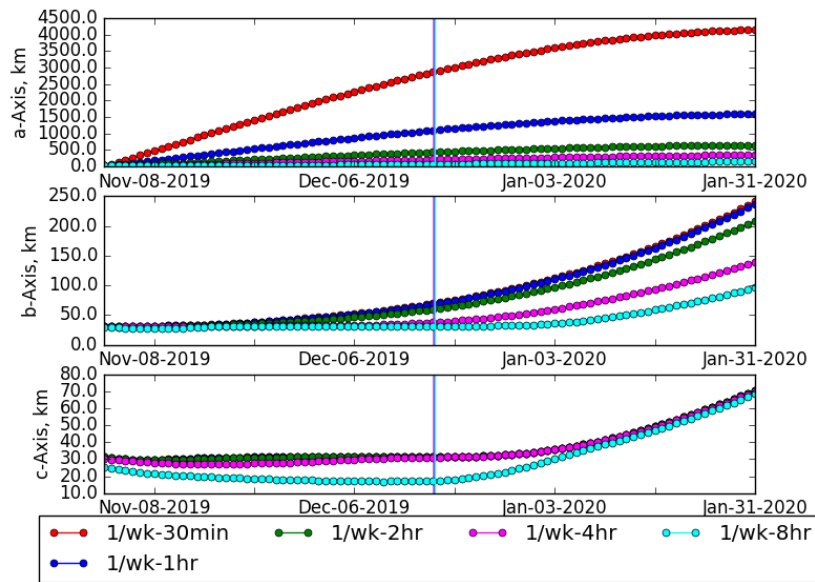
Doppler + DDOR

Doppler 2- vs 1-way

1 pass / week, position uncertainty



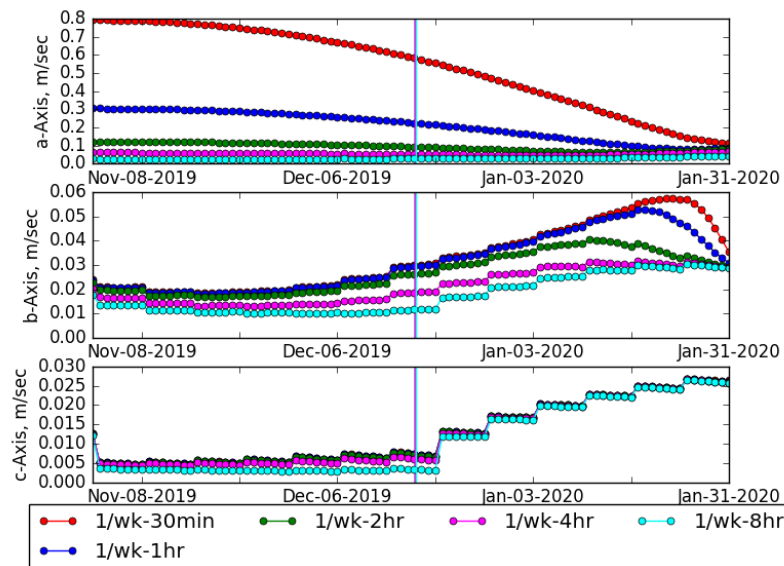
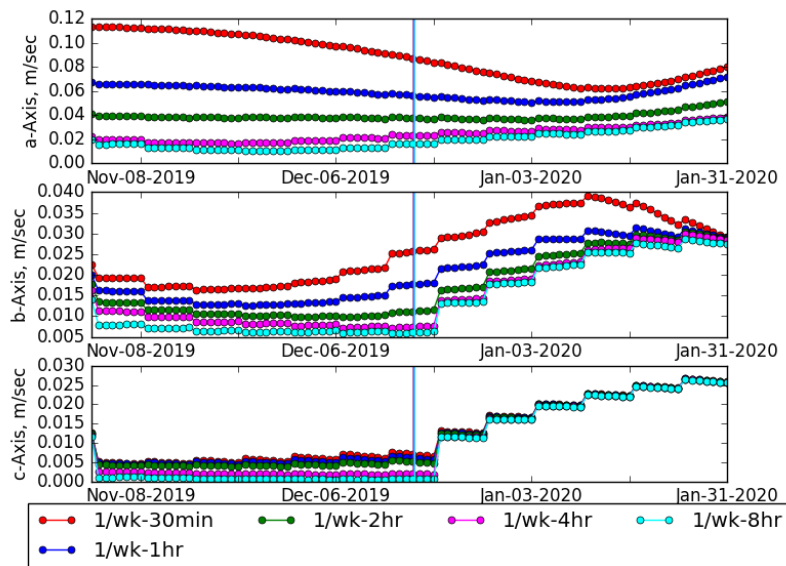
2-way



1-way

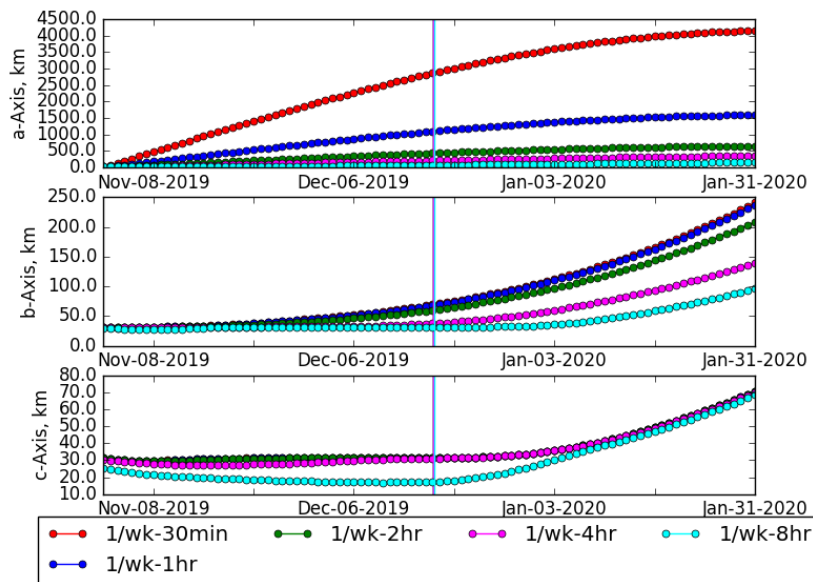
Doppler 2- vs 1-way

1 pass / week, velocity uncertainty

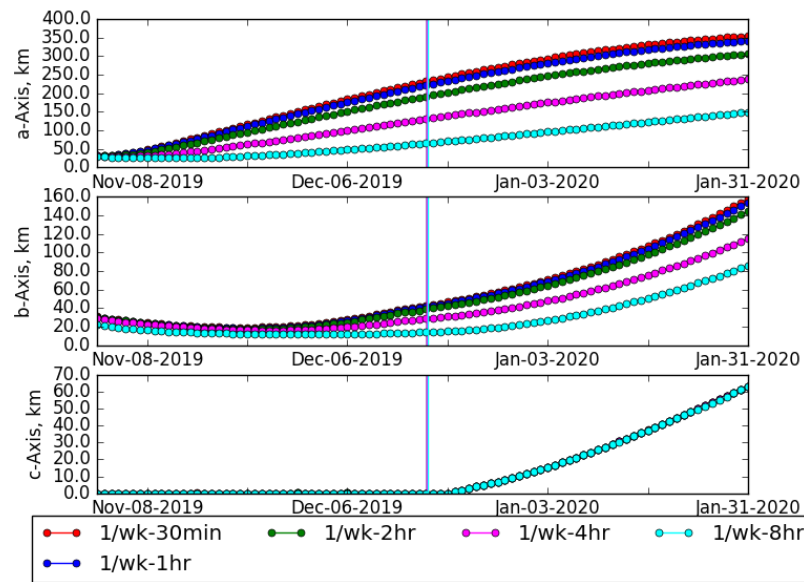


1-way Radiometric Tracking

1 pass / week



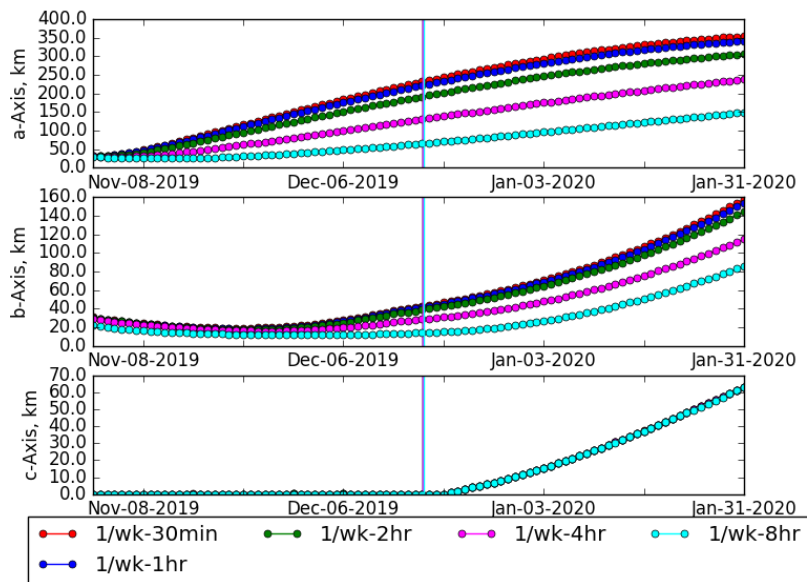
Doppler only



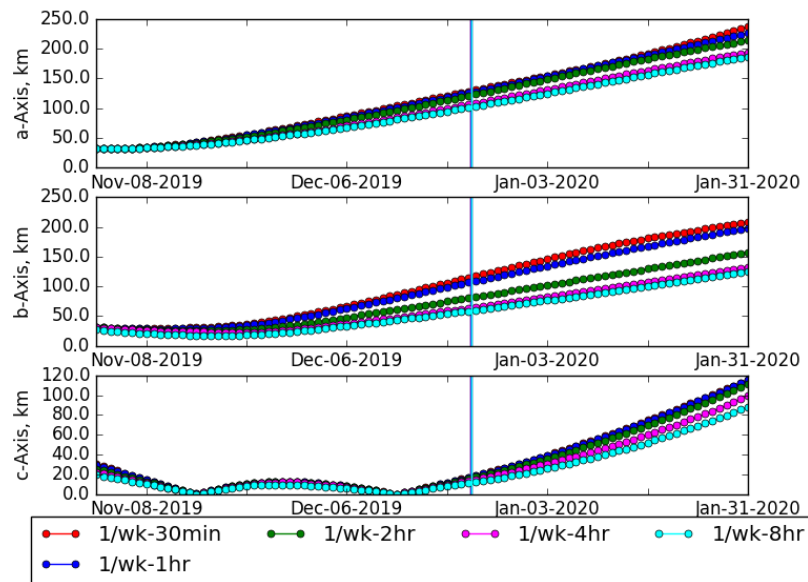
Doppler + Range

1-way Doppler + (Range/DDOR)

1 pass / week, 1 DDOR / week



Doppler + Range



Doppler + DDOR